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"CONTRIBUTION TO THE STUDY OF RADIO NOISE GENERATED BY MEDIUM VOLTAGE LINES"

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Giving account of work showing the possibility of evaluating the radio noise fields created by high frequency currents which are generated by insulators on medium voltage lines. In the first part, the authors analyze the process of forming these currents both in rigid insulators and then in suspension insulators; they show that the spectrum of the disturbing current is characterized by the line geometry and by the capacitance between the two metal parts of the insulator. An equivalent circuit of the insulator and line proves that they behave as a current generator injecting high frequency current in the two halves of the line on each side of the insulator. This current, determined by a series of laboratory tests, is the principal characteristic of insulator noise.

In the second part of the article, the authors reveal the possibility of obtaining correlation between the disturbance field measured under the medium tension line and the disturbance current injected in the line and determined from laboratory tests. A formula is established allowing the prediction of attenuation of the disturbance field in a direction perpendicular to the line as well as the absolute value of the disturbance field.

PART I: STUDY OF INSULATORS

Radio noise disturbances observed under lines of medium voltage cannot be attributed to the conductors, as is the case for high voltage lines, because the gradient to which they are subjected, of the order of 3 to 6 kv/cm, is much too low to generate, except during rain, leakage currents caused by corona. In the present work, we propose to demonstrate the possibility of evaluating the disturbance field of a medium voltage line due to the insulators, basing it on the laboratory measurements of the high frequency currents generated by the latter.

I. THEORETICAL STUDY OF INSULATORS.

Experience shows that the disturbance field of a medium voltage line does not vary in the same way, depending on whether the line is equipped with rigid [pin?] or suspension insulators: in the first case the disturbance field decreases markedly in fog or rain, whereas the opposite occurs beneath lines with suspension insulators. It seems then that insulators are, according to their type, the seat of different phenomena, phenomena that we are going to attempt to explain in what follows:

A. Rigid Insulators [pin type?]: - In the case of rigid insulators, the conductor is simply supported at the insulator neck by a lashing-like attachment, so that, if some portions of the conductor are in intimate contact with the insulator body, others must be separated by small air gaps. Because the insulation resistance is very high, it is justifiable to represent by independent capacitors the lines of force bordering on the zones of intimate contact and the lines of force bordering upon the air spaces. The same representation is valuable in the case of a defective insulator, where air gaps are caused by cracks in the insulator body or in the cement of the metal support.

The equivalent circuit is the following (fig. 1). When the voltage applied between A and B varies sinusoidally, practically all of it is carried by the air-gap terminals 1-2, 3-4. It produces then small sparks which charge C_1---C_2, in an extremely short time, and which are the origin of the disturbance. During fog or rain, it is conceeded that the small air gaps existing at the insulator surface must be short-circuited by water drops: then sparks do not occur, causing the disturbance to disappear. On the other hand, the discharges produced in the cracks continue; as they have, in addition, large amplitudes, it is possible to detect defective insulators by all methods sensitive to an effect external to the phenomena.

Granting that the short circuit of these gaps starts instantaneously, each of them may be represented analytically by applying to the terminals of the gaps, at the instant 0, a voltage step equal in value and opposite to the steady-state voltage at this instant. As one is only interested in the transient operation generated by the start of sparking between 1 and 2 for example, it is necessary to disregard all steady-state currents and voltages and this results in, according to figure 2, Z representing the characteristic impedance of each half line which goes away from the insulator.

$$i = \frac{1}{2} \frac{VC_1}{(C_0 + C_1)Z/2} \exp\left[- \frac{t}{(C_0 + C_1)Z/2}\right].$$

where $C_1 \ll C_0$, this may be written

$$i = \frac{VC_1}{ZC_0} \exp\left[- \frac{t}{ZC_0/2}\right].$$

B. Suspension Insulators (Cap and pin, isoblocks, etc.). - Experience has shown, in this case, the disturbance field increases with rain or fog, it is attempted to explain the disturbance phenomenon by the same process which occurs on high voltage lines: at points of very high gradient, plumes are produced corresponding physically to instantaneous emission into adjoining space of positive or negative electric charges (ions or electrons). The deposit of water drops on the insulator fittings under voltage again re-enforces these local gradients and multiply the points where they appear, which increases the number and amplitude of the discharges.

The equivalent circuit of an insulator and line, always from the transient-state view point, is then represented as follows (fig. 3): at the start, supposed to be instantaneous, of a charge q corresponding to the instantaneous appearance of a voltage q/C_o at the terminals of the insulator capacity. Applying Thévenin's theorem, it is deduced that it acts as though the insulator were a voltage generator, with an internal impedance defined by C_0 and supplying a step voltage of q/C_0; the expression for the current injected in each half of the lines is

$$i = \frac{1}{2} \frac{q}{C_0 Z/2} \exp\left[- \frac{t}{C_0 Z/2}\right]$$

or

$$i = \frac{q}{C_0 Z} \exp\left[- \frac{t}{C_0 Z/2}\right].$$

C. Discussion. Value of the spectral components.

The comparison of the expressions obtained for the two insulator cases makes evident a remarkable fact that, whatever the hypothesis considered, the current injected in the line has rigorously the same behavior represented by an exponential function with a time constant $\frac{C_0Z}{2}$. Physically this exponential behavior corresponds to equalization of the charge emitted by the insulator capacitance C_0 across the impedance Z/2 resulting from the two half lines. The difference lies in the fact that the charge lost by the suspension insulator designated by q is absorbed by ambient space, while the charge lost by the capacitance C_0 of the rigid insulator is absorbed by the small capacitance C_1 and has a value VC_1 (granting $C_1 \ll C_0$).

Thus, these phenomena, which are of fundamentally different physical nature, should in analysis appear as being mathematically identical. The equations which define the behavior of the insulator with respect to the line are the same in the two cases, whence the result that the disturbance field of a line on one hand, and the conditions of laboratory measurement on the other hand, obey the same rules which are the type of insulator or the hypothesis of generation of the disturbance considered. Consequently, from the strict viewpoint of mathematical analysis of the phenomena, there will be no consequent need to take account of their physical nature.

Now evaluating the spectral density of the current pulse injected in the line by application of Fourier's transform

$$g(\omega) = \int_{-\infty}^{+\infty} i(t)e^{-j\omega t}dt,$$

that is

$$g(\omega) = \frac{q}{C_0Z}\int_0^{\infty} \exp - t\left[\frac{2}{C_0Z} + j\omega\right]dt$$

(it is sufficient to integrate from $t = 0$ to $t = \infty$, since by definition the pulse is zero for $t < 0$).

Then

$$g(\omega) = \frac{q}{2}\,\frac{1}{1 + j\omega\frac{C_0Z}{2}}.$$

In reality the insulator does not produce a unique pulse, but series of pulses of variable amplitudes, and groups in "bursts" which generally repeat twice in each period T of the supply voltage, with a certain dispension around the average repetition time.

We classify these pulses in categories corresponding to discharges of average amplitude $q_1, q_2, \ldots q_i \ldots q_n$ and assuming for each category an amplitude coefficient $\lambda_i < 1$ corresponding to the maximum discharge q. Designating, on the other hand by σ^2 the square of the average deviation in time corresponding to the repetition period T_i. This gives

$$G^2(\omega) = \left[1 - \exp(-\sigma^2\omega^2) + \exp(-\sigma^2\omega^2)\,\frac{2\pi}{T}\delta\left(\omega - \frac{2m\pi}{T}\right)\right] \text{X}\ \frac{[g(\omega)]^2}{T}\sum_0^N \lambda^2{}_i$$

where δ is Dirac's function which makes the second term in the bracket zero except for harmonics of $\frac{2\pi}{T}$.

The spectrum is analyzed into a line spectrum with the amplitudes decreasing very fast with frequency, and into a continuous spectrum.

At radio frequencies (broadcast and television) the term $e^{-\sigma^2\omega^2}$ becomes negligible, there is no line spectrum and most simply

$$G^2(\omega) = \frac{1}{T}\,\frac{q^2}{4}\left[\frac{1}{1 + j\omega\frac{ZC_0}{2}}\right]^2 \sum_0^N \lambda^2{}_i.$$

All radio receivers of the type used for our studies are characterized by a band width $B = \Delta\omega$, which are sensitive only to a fraction of the energy spectrum centered on the frequency ω_0; in other words, they respond only to the energy in the band between $\omega_o - \frac{B}{2}$ and $\omega_o + \frac{B}{2}$. Parseval's theorem shows us that this energy is proportional to the band width; the quadratic value of the current "seen" by the receiver from the frequency ω_0 is

$$i^2(\omega_o) = BG^2(\omega_o),$$

since B is sufficiently narrow to consider that $G(\omega)$ is constant in the frequency interval.

The measurements of fields and currents conform to CISPR standard and give a reading proportional to current crest; for a given band width and type of signal in question assuming they have a corresponding constant k relating the crest and effective values, the measuring equipment indicates a current

$$i(\omega_o) = \left[k\frac{q}{2}\sqrt{\frac{B}{T}\sum_0^N \lambda^2{}_i}\right]\frac{1}{1 + j\omega_o\frac{C_oZ}{2}}$$

Designating by i_o the term in brackets, which represents a current amplitude independent of frequency, we finally measure a current

$$i(\omega_o) = \frac{i_o}{1 + j\omega_o\,\frac{C_oZ}{2}}$$

It is this current $i(\omega_o)$ which, in all the following of this study, we designate as "insulator disturbance current at frequency $\frac{\omega_o}{2\pi}$".

From this last expression, we are able to make some observations that are extremely important in interpreting the experimental results.

1. Everything occurs as though the current of the amplitude found, independent of the frequency, were injected at a point P of the combination of the line impedance and the insulator capacity. This concept is fruitful, because it allows the behavior of the line to be accounted for by the external injection of a known artificial current (fig. 4).

2. The current injected in the line is practically constant, as a function of frequency, up to a frequency as large as

$$\frac{\omega C_0 Z}{2} = 1$$

or

$$f = \frac{1}{\pi C_0 Z}$$

Beyond this frequency "of cut-off" the amplitude of the measured current decreases at a rate of 6 db per octave. The spectrum which is recorded is not a characteristic spectrum of the insulator or the discharge, but is determined by the association of its capacitance with the impedance of injection in the line. This discovery is fundamental for comparing spectra obtained from laboratory measurements and from direct measurements of the disturbance fields beneath lines.

3. Television frequencies are far beyond the highest cut-off frequency defined. At these frequencies, the current injected in the line by an insulator, is reduced considerably in comparison to the value i_o for low frequencies. This is one of the fundamental reasons (but not the only one, we will see others later) why television disturbances created by an insulator have an entirely local effect, and will not be transmitted by the line.

A numeric example will define the order of magnitude

Let $C_0 = 100$ pF and $\frac{Z}{2} = 300$ ohms. The cut-off frequency has a value $F_0 = 5$ mc; at 100 mc the attenuation has become 26 db (1/20).

II. EXPERIMENTAL PROOF OF THE THEORY. -

Related to checking at what point the theoretical considerations which were developed are valid, we have had certain experiences which we are going to describe. They bear on the following points:

A. Experimental curves of spectra;

B. Displays of current pulses and photographs of discharges;

C. Artificial reproduction of the disturbance phenomena.

For these measurements we have adopted the circuit shown in fig. 5b which moreover corresponds, with some variations, to the circuit recommended by CISPR.

The insulator tested (rigid or suspended type) is fastened to a metal support aligned to the body, representing the pole, and supports a bar, placed under voltage which represents the conductor. The bar, 10 mm in diameter, is smooth and terminated by a small sphere to avoid corona.

The circuit, which is the so-called measuring circuit, from the viewpoint of high-frequency transients is equivalent to the theoretical circuit, the only difference is due to the presence of the capacitor C_m which blocks the 50-cycle supply voltage from the branch to ground. When it is connected in the circuit, it modifies the amplitude of the disturbing current at the cut-off frequency, in accordance with the new expression

$$i_m(\omega) = \frac{i_o}{1 + \frac{C_o}{C_m} + j\omega RC_o} ;$$

It is possible to take into account the presence of this capacitor if its capacitance is very small compared to C_o, but it suffices that it equals 5 C_o for then it may be neglected: it is necessary to specify that C_o is not made up only of the insulator but equals the capacitance of the connections (bar under voltage and sphere) and by the parasitic capacitance of the mass of the capacitor C_m itself; these elements entering the computation of the cut-off frequency of the spectrum.

On the other hand, it is important to note that the decoupling capacitor must have an inherent inductance as small as possible, at the expense of not providing the correct spectral analysis of the pulses up to high frequencies: in effect an ordinary capacitor of oil-impregnated paper gives a frequency of the order of megacycles which is the limit of its usefulness. Hence we have used a special capacitor of 1000 pF made of an assembly of dielectric ceramic in oil, which reduces its inductance to that of the leads. The resonant frequency of the high frequency circuit has then become 15 or 20 mc, as is shown by curves of capacitance vs. frequency obtained with a Q-meter (fig. 6).

The resistor B is of the order of 20 k ohms, which has the purpose of decoupling the measuring and 50-cycle supply circuits; its advantage in the rejector circuit recommended by CISPR is to provide uniform decoupling at all frequencies without needing adjustment.

Finally, the measuring apparatus used in the Siemens 3800 meter, meeting CISPR specifications, will measure the high frequency current injected across the resistor R.

A. Study of spectra. - We have plotted, for a rigid insulator type HT 30 and for a suspension insulator type CT 175, a series of spectra of this current $i = f(\omega)$ with respect to many values of resistance R (fig. 7 and 8). It is found that the general form of the spectra remarkably agree with that predicted by theory: first a region where the current is independent of frequency, then after a bend joining the cut-off frequency, a decrease of field of 6 db per octave. The displacement of the cut-off frequencies toward the left, at increasing resistances, as well as the parallelism of the right-hand slopes, appears in a particularly clear manner.

Comparing the cut-off frequencies obtained experimentally with those which calculation gives, take into account the values of charging resistance and apparent capacitance of the circuit (measured with a Q-meter) (fig. 8), one obtains Table I.

TABLE I

Comparison of the calculated and measured
values of cut-off frequencies

Resistance R (ohms)	CT 175 $F_o$mc		HT 30 $F_o$mc	
	Calculated	Measured	Calculated	Measured
15,300	0.10	0.10	0.13	0.15
6,200	0.26	0.30	0.32	0.30
2,250	0.70	0.60	0.90	0.80
600	2.7	2.0	3.3	2.5
210	~ 5.0	~ 4	7.5	~ 6

For high resistances, a very good agreement is found between the experimental and calculated cut-off frequencies.

At about 600 ohms, the measured cut-off frequencies appear systematically smaller, a phenomenon for which we have not found a satisfactory explanation; perhaps other damping elements exist in the circuit (proximity of iron pieces, skin effect...) having the effect of increasing the total value of circuit resistance.

In relation to resistances less than 200 ohms, the theoretical cut-off frequency reaches the normal resonant frequency of the circuit, and its calculation does not make sense; we have studied the evaluation taking account of the apparent increase of the capacitance, values are found agreeing well with measurement, but the spectrum does not have the theoretical shape, and in particular, the inclined zone falls at a slope greater than 6 db per octave, which occurs at resonance.

B. Visualization of the pulses. - Photographs of discharges. - We have seen in the preceding section, that the spectrum, which is recorded when the insulator subjected to voltage generates disturbances, results from the superposition of a great number of pulses of identical individual shape, but variable amplitudes, and whose position is distributed about the average repetition frequency according to a law of stationary risk. Equally we have seen that the total spectrum must have the same behavior as the spectrum of a single pulse. The verification of the pulse shape constitutes another confirmation of our hypothesis because of the relation known to exist between the spectrum and pulse shape, in addition the latter has been established by calculation.

To this effect, we have used a special oscillograph, with vertical amplifier presenting a band width of the order of 50 mc; this permits reproduction without distortion of fronts that have a "rise time" of 6×10^{-9} seconds.

The lead of this oscillograph should be connected to terminals on a portion of the resistance R, in a manner to assure its correct use; thanks to a delay cable it will be possible to adjust the triggering and duration of the sweep so that the entire pulses will be visible on the screen. Thus it is easily possible to perfectly observe the shapes whatever may be the amplitudes of the successive pulses.

In regulating the sensitivity of triggering so that only the largest pulses are recorded on the screen, it has been possible to note their form precisely as is shown by the oscillograms of fig. 9.

The cut-off frequencies f_o of the spectra and the time constant of the pulse tails T_o are related by the theoretical relation $2\pi f_o T_o = 1$ although crossover between values recorded from spectra and the pulse shapes may not be rigorous, it is again found to be between compatible orders of magnitude. On the other hand, the wave front rise time of the order of 20 ns explains the begining of the very steep slope of the spectra starting at about 20 mc. Regarding the pulses showing a superposed slightly damped oscillation, at a frequency of the order of 20 mc, which are shown by spectra around this frequency: this has been shown to correspond to a resonance in the high frequency circuit, preceding the steeper fall off of the spectrum.

In parallel with these measurements, we photographed the insulators under voltage in darkness to reveal the location of the discharges.

In this concern the pin insulators (type HT 30) have been usually observed to produce small sparks at the neck where the conductor is attached, the number increasing in proportion to the increase of voltage.

In figure 10 which has been taken at a voltage well above normal to better show the nature of the phenomenon, these sparks form a luminescent ring. On the contrary the phenomenon totally disappears in rain (fig. 10b), also at very high voltages, at the limit of the insulator contour.

In this concern the suspension insulator (glass insulators CT 175), it seems that the disturbance starts by the formation of corona beneath the skirt (fig. 10C), short circuiting the cement between the pin and the glass: the phenomenon then appears to be of the same nature as for the rigid insulators, that is charge of small capacitances through air which is energized. At increased voltage, the corona appears equal beneath the skirt and at the level of the cap (fig. 10C). With rain the upper corona disappears, the lower corona increases markedly; it is certain to come from water drops (fig. 10d).

Finally plumes from the conductor are not observed.

C. Artificial reproduction of the disturbance phenomenon. - To allow direct work on the parameters controlling the shape of the disturbing pulses, we made the following setup (fig. 11), which synthesises the high frequency transient behavior, without the necessity of applying high voltage: the insulator must always be in the setup described, the excitation of the air gap has been replaced by periodic closing of a vibrating electromechanical relay ("Clare" having wetted contacts, to prevent chatter) charging a capacitor C_1 of exactly 5 pF. A dc source of 100 v represents the quasi-steady state voltage applied to the insulator: the 50 mega-ohm resistance r is to discharge C_1 between successive closures of the relay to assure consistency.

For these new conditions we have made oscillographic observations of the wave form over a wide range obtained at the terminals of resistance R: we observed the very same wave shapes as with high voltage: in particular to again find the pulse front of 20 nS, the charge on C_1 must be damped by a resistance of the order of 5,000 ohms. This must be explained by the fact that the elementary capacitance in the actual phenomenon is made up of flux lines that terminate on the very highly insulating surface greater than the impact point of the spark; the charges which dissipate relatively slowly, because of the surface resistance, which damps the front (fig. 12).

Under the same conditions, we have traced spectra for many values of resistance R; the appearance of these spectra is seen to coincide remarkably well with those of the actual disturbances (fig. 13).

The following results were obtained:

Resistance (ohms)	$T_o = \frac{1}{2\pi f_o}$ obtained from spectra (ns)	T_o from oscillograms (ns)
210	30	30
600	80	100
2,200	270	300
6,000	800	800
15,300	~2,000	2,500

III. SYSTEMATIC MEASUREMENT OF INSULATOR DISTURBANCE LEVELS. -

A. Circuit used. Mode of operation. - For this series of measurements we have again used the general circuit and material which we have described. The arrangement of the insulators is the same; we must respect the actual distribution of the electric fields by choosing supports of suitable dimensions.

The measuring resistor of 300 ohms conforms to the CISPR standards, all values have been taken at a frequency of 1 mc. It is seen from the spectra we have taken that, at this frequency taking the capacity of the test piece into account, the disturbance level corresponds to the horizontal part of the spectrum; i.e. is independent of frequency.

In accordance with practice, the levels are expressed by the disturbance voltage on the 300-ohm resistor (we will see later that this value is not of much significance, but that the value which enters the calculation of the field under a line is the disturbance current injected by the insulator). In this connection it is noted that the readings must be made of complete cycles of increasing and decreasing voltage, and, for each measurement the disturbance field stabilizes after waiting for ten minutes: only under these conditions a proper superposition of increasing and decreasing current is observed; it is well known that this is caused by burning off contaminants by corona which in fact corresponds to an "aging" of the disturbing element.

B. Test results. - The tests have been made for the operating conditions of a new line: insulators in good condition with correct ties.

The material studied consists of (fig. 14):

three chains of suspension insulators CT 175 (glass);

a chain of suspension insulators CT 175 (porcelain);

rigid insulators HT 30 with re-enforced crossties, or with ties in an arch;

porcelain monoblock insulators:

a) with four skirts and ball-and-socket attachment;

b) with three skirts and shackle or ball-and-socket;

c) a spiralex insulator;
a cable only, and with a broken strand (7-strand almélec).
<7-strand electrical grade aluminum>

Measurements were made under the following climactic conditions:

"warm: : temperature 32°C hygrometric degrees 30 for 100 per cent;
<perhaps 30 per cent relative humidity>

"dry" : temperature 18°C hygrometric degrees 50 for 100;

fog : temperature 14°C hygrometric degrees 100 for 100;

normal rain: temperature 20°C hygrometric degrees 100 for 100.

Different arrangements of the same type (cap and pin monoblock, monoblock rigid) are shown to behave in a practically identical manner, with a small variation in practice which makes it practically useless to give the results.

In Table II we have for clarity simply shown the most significant average values obtained for voltages of $15/\sqrt{3}$ kv and $20/\sqrt{3}$ kv corresponding to network voltages of 15 kv and 20 kv.

TABLE II. - Average values obtained

	Equipment							
	String of 3 insulators CT 175 µv		Isoblock insulators µv		HT 30 insulators µv		Cable almélec	
(*) Test condition	15 kv	20 kv	15 kv	20 kv	15 kv	20 kv	15 kv	20 kv
warm					500	900		
dry	1	1	1	2	400	700	Not measurable	
fog	1	2	4	5	2	2		
rain	6	20	10	10	8	20		

*Values less than 10 µv, below the threshold, have been extrapolated.

The curves (figures 15 to 19) show how the disturbance field varies for several types of material as a function of voltage and for several climactic conditions.

The following curves result from this series of measurements.

The rigid insulators <pin insulator> under normal conditions and voltage have an appreciable ionization level in a dry condition. Under rain and fog the field decreases below the threshold of measurement (<10 µ v). At 15 to 20 kv the disturbance field approximately doubles.

In this concern the suspension insulators (cap and pin or isoblock), the level found in the laboratory is always less than or of the order of the measurement threshold except with some exceptions under rain.

The conclusions made up to the present and the hypotheses from which they were deduced have on the whole been well confirmed, namely:

a) the disturbance field of the rigid insulators which is relatively important "dry" decreases to a negligible value with rain or fog;

b) the disturbance field of the suspension insulators is higher with rain than dry, but is generally less than that of the rigid insulators;

c) in each case, plumes which determine the disturbance level of the medium tension line do not form on the conductors: their only role is to propagate the disturbance currents.

Although the laboratory tests described account well for the behavior most frequently observed under the lines, it seems that the actual levels are a little higher than those which will be predicted; on the other hand, several important differences are apparent which can probably be explained by more extended laboratory tests taking into account the particular circumstances under which these differences have been observed and we will only cite that of intense sunlight. These several points will be explained in the second part of this article.

PART II: DISTURBANCE FIELD OF MEDIUM VOLTAGE LINES

I. PHYSICAL REPRESENTATION OF THE PHENOMENA AT WORK

We have now seen that the transient phenomena of which the insulators are the seat are manifested by two current waves injected in the conductors and propagating themselves in opposite directions on each side of each insulator. We have equally seen that these current waves, at a very steep front at their origin, may be analyzed in a Fourier spectrum; now the components of this spectrum behave in very different fashions, according to their frequency band, and this behavior has a direct influence on the way receivers are disturbed in the vicinity of the line. In general, the phenomena may be represented as follows.

So long as the wave length of the spectral compared is large because of the transverse dimensions of the line, that is to say to the extent of the transverse propagation of voltages, one can consider that at this component of current there are associated two orthogonal fields, one electric the other magnetic, which propagate together along the line, they form a plane (guided) wave, whose energy vector is parallel to the line. The attenuation, which increases as a function of frequency, is sufficiently small for the disturbance to thus transmit only for distances of several kilometers.

When the wave length becomes of the same order of magnitude as the transverse dimensions of the line, that is to say, when it is necessary to introduce the concept of retarded potential, bringing into play an altogether different process: part of the energy is radiated directly by the line, acting as an antenna, in the form of an electromagnetic wave, at the same time which with frequency increases the conductor lengths participating in this radiation around the point of generation being reduced more and more.

At television frequencies (above 50 mc) it is not a practiacl wave guide, but only electromagnetic radiation of a more or less very local sphere of action.

Thus the high frequency energy generated by an insulator propagates in two entirely different manners. It must flow out along the line, by which it is guided, called "channel disturbance" (this is the case for long and medium waves), being radiated from the insulator as a space wave, referred to as direct radiation (this is the case of ultra short waves). The short waves participate in the two types of propagation simultaneously.

From the preceding analysis it results that for the long and medium waves, the dominant part of the disturbance field is caused by the superposition of the effects of all insulators distributed along several tens of kilometers on each side of the point of measurement, and not on the direct effect of nearby insulators.

To the contrary for very short waves (television), the disturbance is not propagated by the line, and has only a local action. As we have seen on the other hand that a sound insulator generates very high frequency current (200 mc) very feebly, a sound line does not normally disturb television. Only a defective element (cracked insulator, bad contact, steady arc) can generate a disturbance which has a local effect for a radius of 200 to 500 meters.

Thus, television disturbances constitute a special case, and it is useless to search for the theoretical value of their level; on the contrary, it is possible to acknowledge that all insulators of a long line present on the average an identical disturbance field, to try to calculate the exact disturbance field for long and medium waves, that is to say for frequencies less than about 5 mc ($\lambda = 60$ m).

II. GENERAL METHOD OF CALCULATING THE GUIDED DISTURBANCE FIELD. -

It was noted earlier that it is easier to reason if the disturbance were a current generator, as we have shown in the first part, it is independent of the loading impedance of the high frequency circuit as long as the spectral frequency studied is less than the cut-off frequency of the pulse spectrum; this is the case for the long and medium waves, taking into account the capacitances of the insulators and the characteristic impedances of the usual three-phase lines.

The current injected in the conductor on both sides of each insulator, induces currents in the nearby conductors whose values depend on the capacities between conductors and in relation to ground. Thus, proceeding from each insulator one obtaines a system of three currents whose propagation must now be studied.

For such a system of any currents, one discovers that a simple law of attenuation of propagation does not exist, the currents and voltages relative to each conductor do not depend on the same relation, and the system undergoes a deformation which is a function of the distance of propagation. But, it is shown that there are particular systems of currents and voltages, called "symmetrical modes" which propagate without deformation and which have a well-defined attenuation constant, thus with the same impedance characteristic common to all conductors. Their value is obtained starting with the potential coefficients of the line considered, resulting in as many modes of propagation for each line as there are conductors. For a three-phase line, the calculation results in three modes of propagation, which we designate

"homopolar mode" - identical polarity on the three conductors symbolized by + + +,

"bipolar mode" - symbolized by + 0 -, and

"interphase mode" - symbolized by + - +

if the line has a flat configuration.

Attenuation of propagation is caused by losses in the earth and in the conductors. It is possible to evaluate the attenuation coefficients relative to each mode, for a given line, it brings in the superficial resistivity of the terrain traversed by the line, the resistivity of the conductors, as well as the geometric structure of the electromagnetic guided field (which is supposed to be a plane wave) associated with the mode considered.

The following formula is used

$$\alpha = \frac{\sqrt{\varepsilon_o}\,\omega}{2\sqrt{2}} \left[\sqrt{\rho_o} \int_{\mathrm{Sol}} \left(\frac{d\phi}{dn}\right)^2 dS + \sqrt{\rho_c} \int_{\mathrm{cond.}} \left(\frac{d\phi}{dn}\right)^2 dS \right]$$

where ρ_o and ρ_c are the resistivities of the earth and the conductors, ϕ is a potential function dependent on the mode considered, and ω is the angular velocity corresponding to the frequency.

When one wants to study the propagation of any system of currents such as we are interested in here, it is necessary to analyze it into symmetrical modes (which have linear properties and consequently can be superposed to constitute the given system) to study separately the propagation of each of them, then recombine at each point of the line the modes which have been obtained after they have independently undergone their own natural attenuation. But in reality, at any point of the line (supposedly infinite) the noise current of each mode considered, is made up by superposing the modal currents due to all insulators on a conductor. On the other hand, it is shown that, because of the random generation of these currents, it is convenient to evaluate the total current by a quadratic summation.

Then α being the attenuation for propagation of the mode considered and i_m being the modal current injected by an insulator, at a distance ℓ from the point of generation, the square of this element of current has a value of

$$dI^2_m = i^2_m \, e^{-2\alpha\ell} . \, d\ell$$

The total modal current obtained is

$$I^2_m = 2i^2_m \int_0^{\infty} \left[e^{-2\alpha\ell} \right] \frac{d\ell}{D} ,$$

where D is the span between adjacent insulators

and
$$I^2_m = \frac{i^2_m}{\alpha D} .$$

Beginning with this total current, and knowing the characteristic impedance of the mode, it is necessary to determine the magnetic and electric components of the field of the ground mode.

The same calculation is repeated for each of the other two modes, and the total disturbance field is finally computed from the quadratic superposition of the three modal fields.

This operation has been made by assuming that each of the insulators on one conductor simultaneously generates disturbance; this is certainly true, since each conductor of a three-phase system reaches its voltage in turn. It is therefore necessary to repeat the calculations separately for each conductor and to compare the ground fields which are obtained in each case, if they are practically equal, the repetition frequency of the noise is multiplied by three, which represents an increase of about 3 db in the CISPR level; if the three fields are not equal, one takes the strongest, increased by a quantity which must be evaluated, but which will always be less then 3 db.

III. SIMPLIFIED FORMULA FOR A MEDIUM VOLTAGE LINE. - PREDETERMINATION OF THE LEVEL. -

When the detailed calculations are made, one verifies that, recognizing the dimensions of a medium voltage line, and because of the supplementary attenuation important owing to the conductors, the disburbance field is practically that of the homopolar mode, the other modes enter little in forming the field at the ground.

This property found only for lines of medium voltage (and which results from the small spacing between the conductors in relation to their distance to earth) contributes a considerable simplification to practical calculation; everything happens as though the line were unipolar and the three currents of the homopolar mode were concentrated in one conductor only. For the usual line dimensions, this equivalent single current has a value in the neighborhood of half the current injected in the half line, being a fourth of the total current injected by the insulator (this holds because the current injected in one of the conductors induces a current of the opposite sign in the other two). The sum of these three currents is then less than the current injected.

The noise current I_p at a point on the line is then given by the simplified expression

$$I_p = \frac{I_{insul}}{4\sqrt{\alpha D}}.$$

The magnetic component of the disturbance field at the ground is obtained (this component is horizontal) by applying Laplace's law and the theory of images (fig. 20);

$$\mathcal{H} = \frac{I_p}{\pi} \frac{h}{h^2 + d^2}$$

where h is the average height of the conductor above ground, and d the distance computed from the axis of the line.

The equivalent electric field in volts per meter obtained from the magnetic field by introducing the concept of the characteristic impedance of space, being $E(V/m) = 120\pi \times H$ (Amp Turns/m) and finds

$$E(V/m) = I_{insul} \frac{30\,h}{(h^2 + d^2)\sqrt{\alpha D}}$$

The reading in decibels (CISPR), calculated taking into account the repitition frequency, then gives

$$N(db) = 3 + 20 \log_{10} E(\mu V/M),$$

if I_{insul} is in microamperes.

The preceding formula may be altered to

$$N(db) = 33 + 20 \log_{10} \frac{h}{h^2 + d^2} - 10 \log_{10} \alpha D + 20 \log I_{insul} ,$$

which permits the influences entering the formation of the real field at the ground to be separated (the first term being a constant, depending on the system of units); the second term accounting for the attenuation perpendicular to the line and determining the form of the transverse profile; the third term accounting for the cumulative effect of various sources of disturbance distributed along the line; finally the fourth term characterizes the intensity of an individual source of disturbance.

These formulas, in a practical way, allow prediction of the disturbance field from the insulators on a line starting with the laboratory measurement of the noise current from an individual device.

IV. APPLICATIONS TO AN ACTUAL LINE. - COMPARISON WITH MEASUREMENTS UNDER THE LINE. -

Characteristics of the line

Service voltage: 15 kv

Average height of conductors above ground: $h = 8$ m

Distance between poles: $D = 64$ m

Homopolar attenuation: $\alpha = 2$ db/km being 2×10^{-4} nepers per meter

Pin insulators type HT 30, triangular arrangement.

Calculation of the profile of this line; the field varying as a function of d follows:

d (in meters)	0	1	2	5	10	15	20	50	100
$20 \log_{10} \frac{h}{h^2 + d^2}$	-18	-18	-18.5	-21	-26.2	-31.2	-35.3	-50	-62
ΔN	0	0	-0.5	-3	-8.2	-13.2	-17.3	-32	-44

The slope of the asymptote is -12 db by doubling the distance. On the other hand, the cumulative effect of the sources contributes

$$10 \log_{10} \alpha D = 10 \log_{10} 64 \times 2 \times 10^{-4} = -19.$$

The field under the line will then be given in final calculation by the expression

$$N(db) = 34 - \Delta N + 20 \log_{10} I_{insul}$$

If the profile thus calculated is adjusted with the real profile recorded under the line, in the first place, the disturbance current of each insulator is deduced from it.

Thus, at the time of measuring beneath the line (the meteorological conditions being: dry weather, $18^{o}C$ temperature, sky lightly covered) the field beneath the center of the line being 44 db at 1 mc (fig. 21). Then one has:

$$44 = N_o = 20 \log_{10} I_{insul} + 34$$

or $20 \log_{10} I_{insul} = 10$ db, which level corresponds at this moment to a disturbing current of 3 μA. This value is in reasonable agreement with those found in the laboratory on the same type of insulators.

In the second place, the comparison of calculated and actual profiles shows an excellent agreement up to about 20 meters, fig. 22. For greater distances from the line, between 20 and 80 m, the slope is only of the order of 9 db for double the distance (which corresponds to a decrease of $1/d^{1.5}$ instead of $1/d^2$. This can be explained by the fact that, rigorously, the other modes are not wholly negligible at these distances, besides the earth is not a perfect conductor, the image of the conductor does not have as clean an effect as in the theoretical calculation; at still greater distances, measurement becomes practically impossible because the natural level of the line is drowned in the background of natural radio noise.

V. VARIOUS OBSERVATIONS AT THE TIME OF MEASURING DIRECTLY UNDER LINES. -

Numerous measurements made beneath other medium voltage lines have shown that, generally, the levels calculated from laboratory tests are weaker than the actual levels.

In this concern, lines with rigid insulators (for example type HT 30), the variation between the calculated level and the measured level ranges between 3 and 10 db; this relatively small variation may easily be interpreted by recognizing that the ties on actual lines loosen because of wind and bad weather, cause more interference than a new tie, well tightened, studied indoors.

In this concern, for lines having suspension insulators (for example type CT 175), some extremely different levels have been noted: when beneath certain lines the agreement with calculation was satisfactory, beneath others variations of 50 db have been discovered. Perhaps these variations are attributable to the effect of insulator polution, corrosion of attachments, oxidation at the position of the ties, which introduce unfavorable conditions are not represented in laboratory tests. To check these points, we now propose laboratory measurement of the disturbance current of ties and insulators taken from lines after a certain time of operation, and for which the disturbance level disagrees with our theory.

Other anomalies have been discovered. In particular, at high temperatures and intense sunshine, an excessive increase in the disturbance level have been observed accompanied by a change in the behavior of the spectrum; intense sunlight seems to favor the generation of high spectral frequencies, without another hypothesis it is not actually possible to explain this phenomenon.

VI. SUMMARY AND CONCLUSION. -

In the first part of this work, we have tried to explain the phenomena of insulator disturbance in mathematical form, finally to analyze the behavior of the assembly constituted by the insulator and the line. To the first approximation, the analytical expression for the disturbance current generated does not depend upon the physical phenomena which is the cause of the disturbance, but nevertheless in a range of frequencies less than some megacycles, is characterized only by the geometry of the line and by the capacity between the two fittings of the insulator.

The experimental studies in the laboratory of the disturbance spectrums have well confirmed this theory. A group of laboratory tests allows determination of the characteristic magnitude of the disturbance effect of the insulator, this magnitude being an intensity of high frequency current injected in the line, without which it would be necessary to make complementary hypotheses on the physical nature of the disturbance.

In the second part we have shown that it is becoming possible to obtain a correlation between the disturbance field measured under the line and disturbing currents injected in the line by the insulators, to take account of the propagation times of these currents and of the cumulative effect of sources of disturbance repeated along the line. The complete calculation is long, but by means of some simplifications justified for lines of medium voltage, one can establish a practical formula for prediction, very simple to use. This formula allows prediction of the attenuation of the field normal to the line (transverse profile) as well as the absolute level of the disturbance field.

Comparison between the predicted fields and those taken under lines show remarkable coincidence of the two profiles. But, in this concern the prediction of the absolute level, measurements beneath a certain number of lines equipped with rigid or suspension [insulators] show the fields derived from laboratory tests are generally weaker than actual fields. This variation can be explained by the fact that insulators on lines are responding to climactic conditions much more severe than insulators tested in the laboratory, some subsequent tests are foreseen to prove this point.

We do not pretend to have explained all of the problems. Many phenomena remain unknown and their interpretation will demand more work and tests.

But in spite of the restrictions which we state, we hope to have contributed to the problem of predicting the disturbance field of medium voltage lines, principally by a better understanding of the mechanisms of injection and propagation of high-frequency currents generated by insulators. It is hoped also that this improved knowledge of the generation of disturbances constitutes only a first step in research on their elimination, the ideal aim to which we must devote our efforts.

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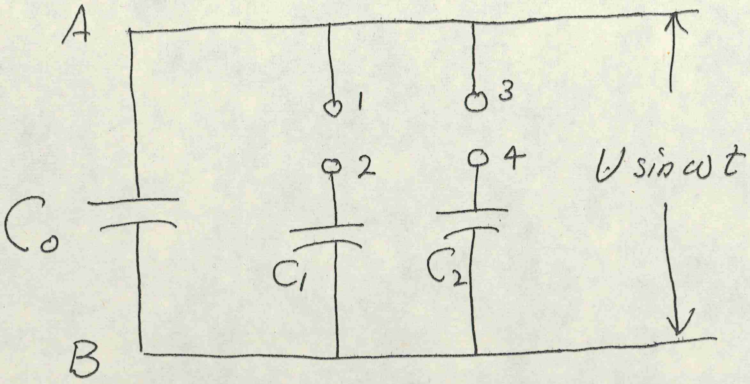

A
B
1
2
3
4
C_0
C_1
C_2
$U \sin \omega t$

Fig. 1. Equivalent diagram of rigid insulator: 1-2, 3, 4, represent spark gaps between conductor and glass, between cement and pin, or internal cracks.

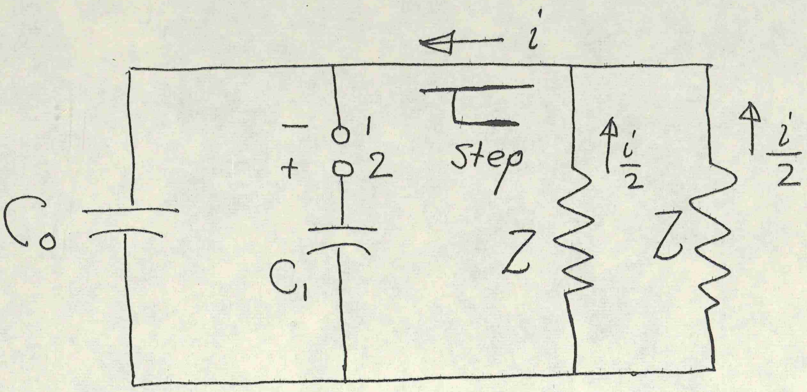

i
−
+
1
2
Step
C_0
C_1
Z
Z
$\frac{i}{2}$
$\frac{i}{2}$

Fig. 2. Representation for transient state caused by sparking of air gap.

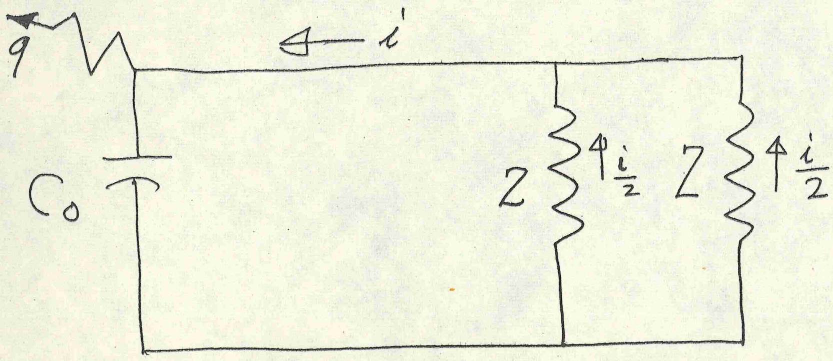

q
i
C_0
Z
Z
$\frac{i}{2}$
$\frac{i}{2}$

Fig. 3. Equivalent circuit of an insulator which causes disturbance by emitting charge to nearby space.

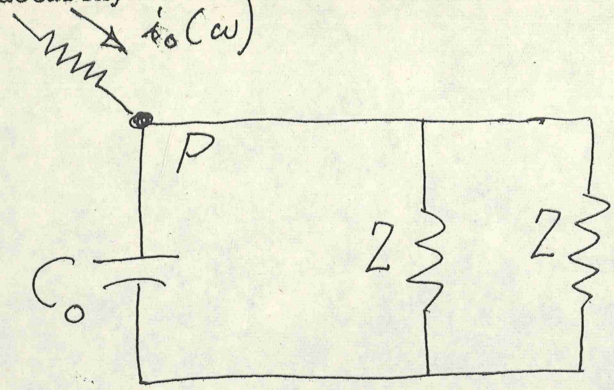


Fig. 4. The instantaneous emission of charge by an insulator is mathematically equivalent to the injection at point P of a current of constant spectral density independent of the frequency.

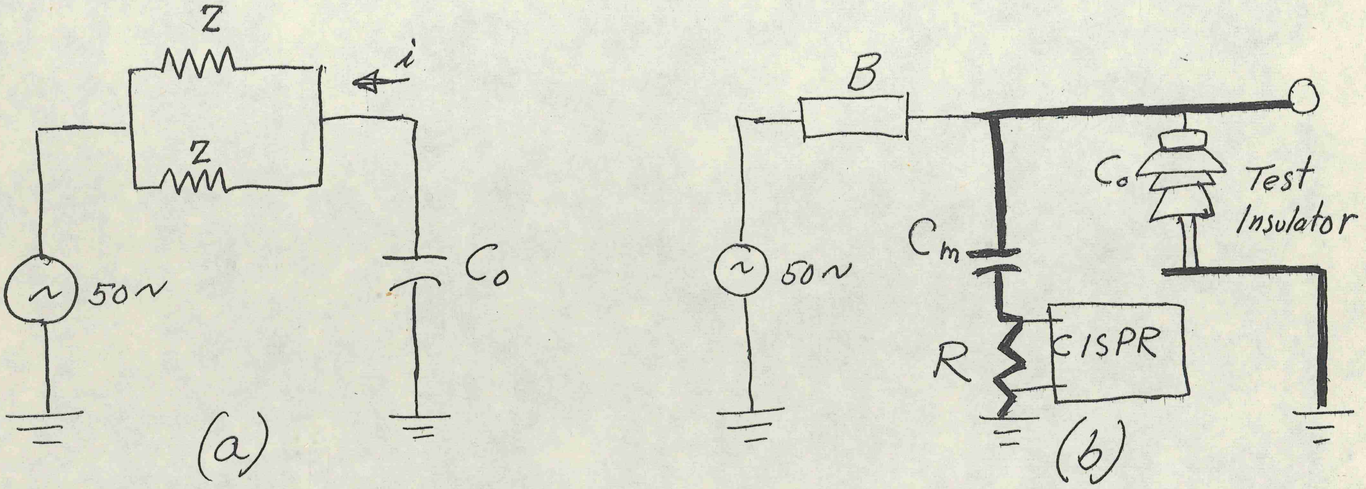


Fig. 5. (a) Equivalent circuit of an actual line subjected to voltage, from the point of view of the production of disturbance currents.
(b) Equivalent circuit of setup used to test insulators: the circuit in heavy lines is for high frequencies equivalent to circuit (a).

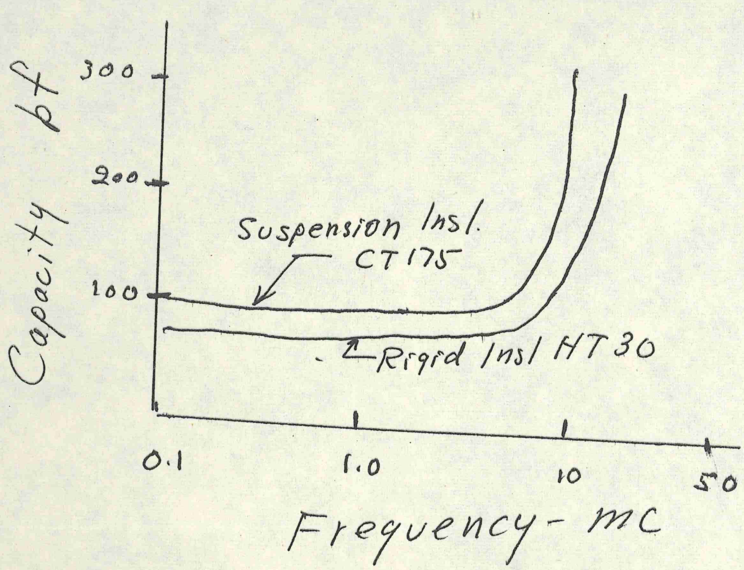


Fig. 6. Curves as function of frequency, for the apparent capacitance of an insulator with its system of attachments and a 1 m portion of the conductor, from the viewpoint of the decoupling capacitor C_m (measured with a Q-meter).

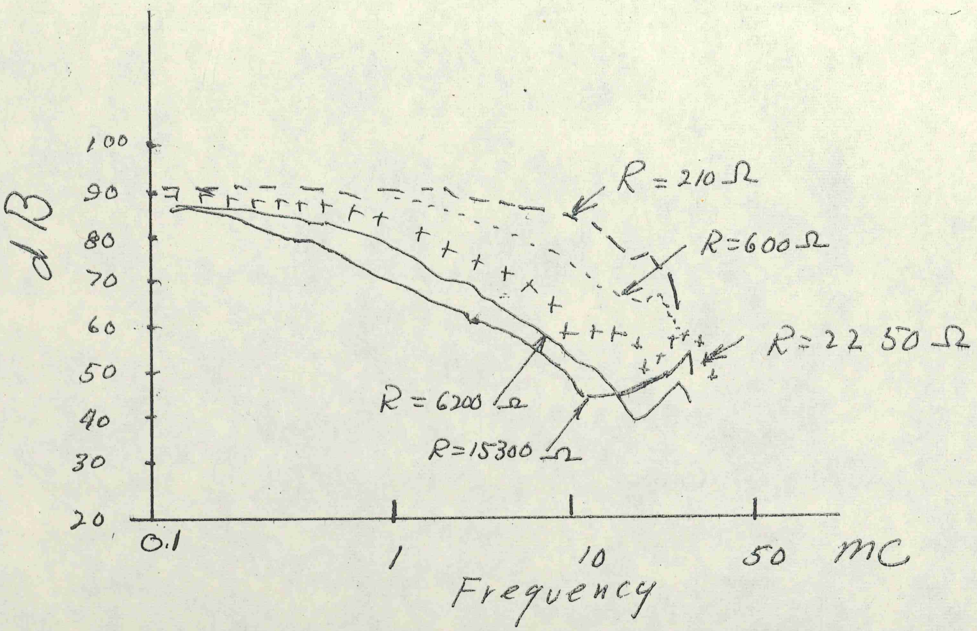


Fig. 7. Spectra of disturbance current for various values of resistor R for a rigid insulator HT 30.

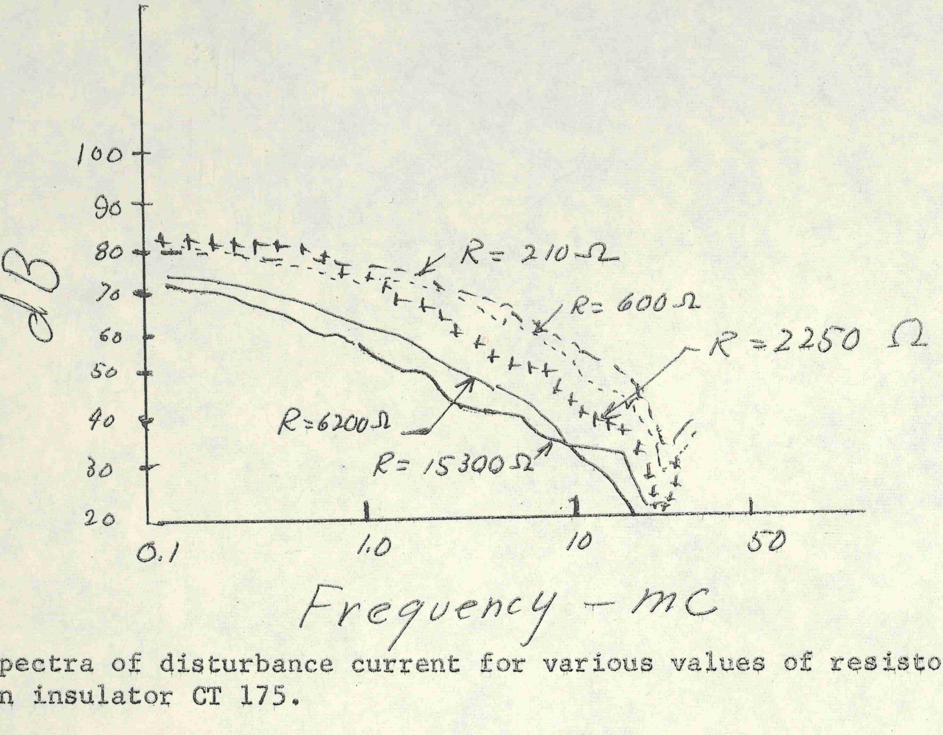


Fig. 8. Spectra of disturbance current for various values of resistor R for a suspense on insulator CT 175.

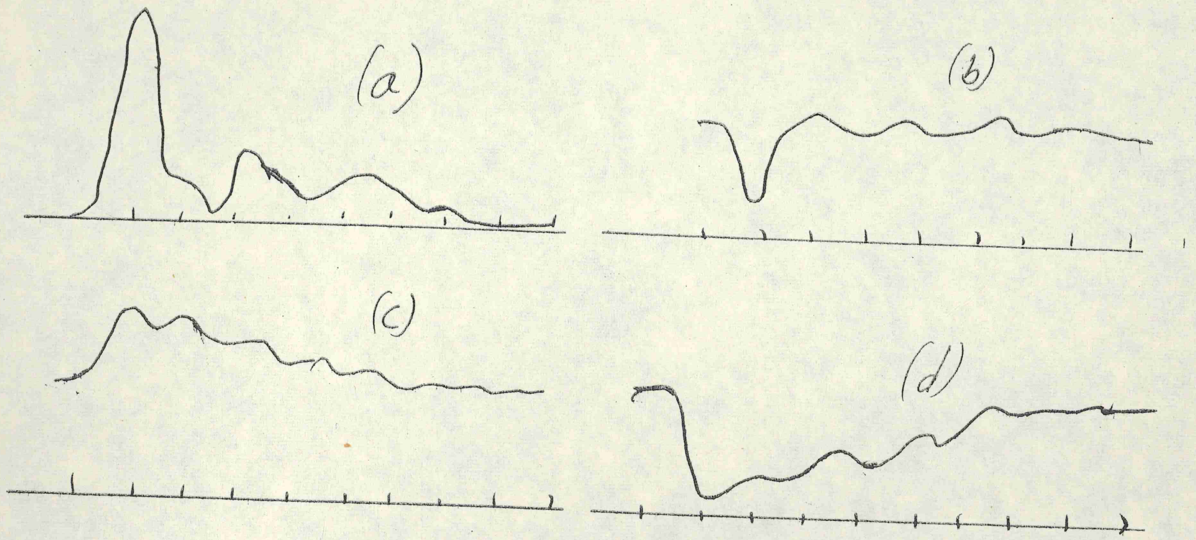


Fig. 9. Oscillograms for disturbance pulses generated by insulators. Suspension insulator CT 175:
a) R = 125 ohms, c) R = 600 ohms; Rigid insulator HT 30: b) R = 125 ohms,
d) R = 600 ohms. (R = discharge resistor.) (Sweep: 50 ns/cm).

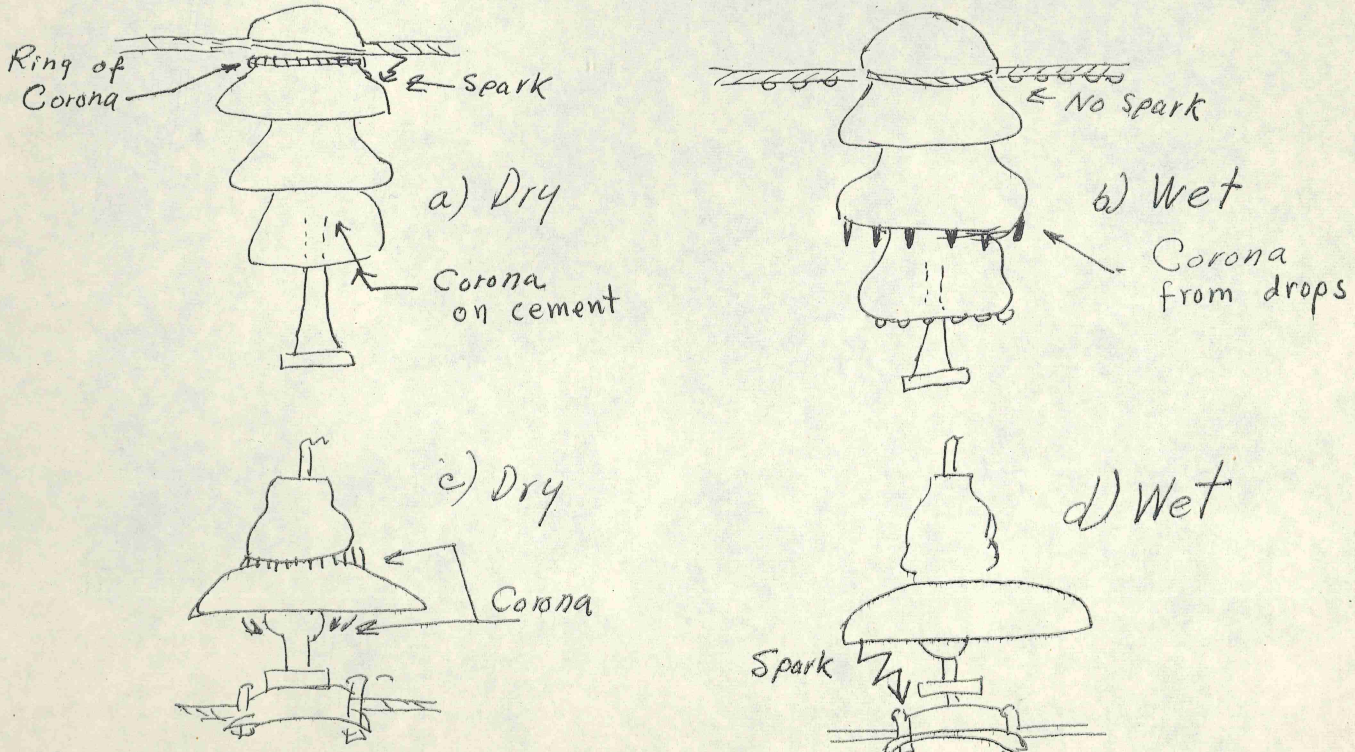

Ring of Corona
Spark
a) Dry
Corona on cement
No Spark
b) Wet
Corona from drops
c) Dry
Corona
d) Wet
Spark

Fig. 10. Views showing the nature and locations of disturbance phenomena on insulators.

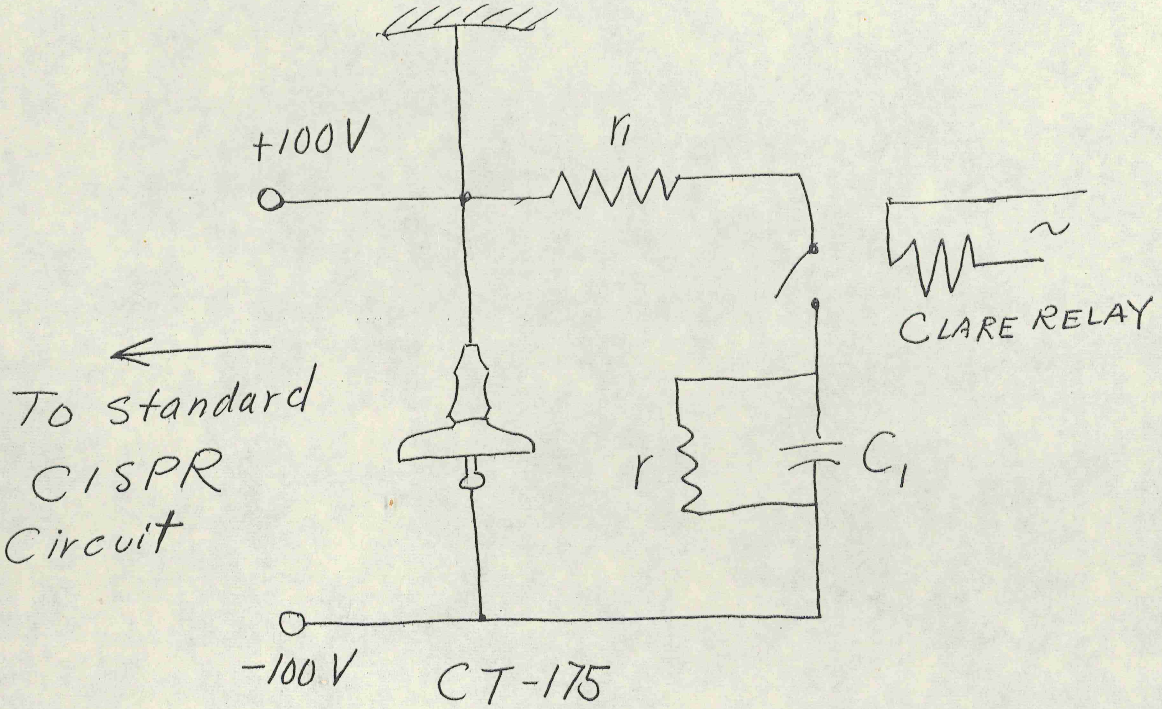

+100V
r1
CLARE RELAY
To standard CISPR Circuit
r
C1
-100V
CT-175

Fig. 11. Setup for the artificial production of disturbance pulses.

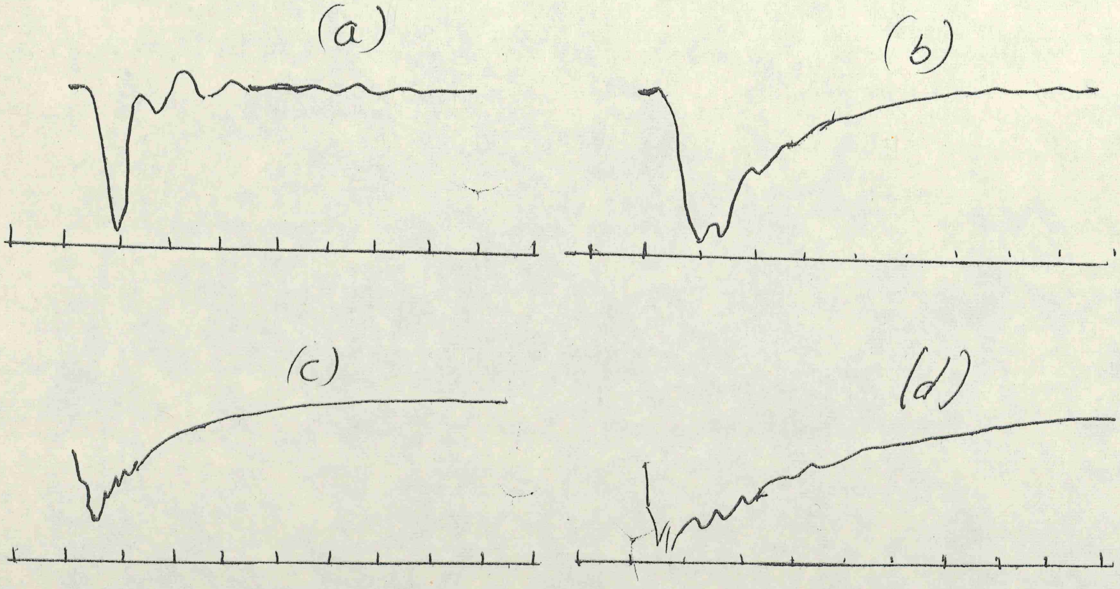


Fig. 12. Oscillograms of artificial disturbance pulses for comparison with natural pulses of figure 9. Suspension insulator CT 175: a) R = 210 ohms: Sweep 30 ns/cm; b) R = 600 ohms Sweep: 50 ns/cm; c) R = 2100 ohms: Sweep 200 ns/cm; d) R = 6000 ohms, Sweep: 200 ns/cm. (R = discharge resistor.)

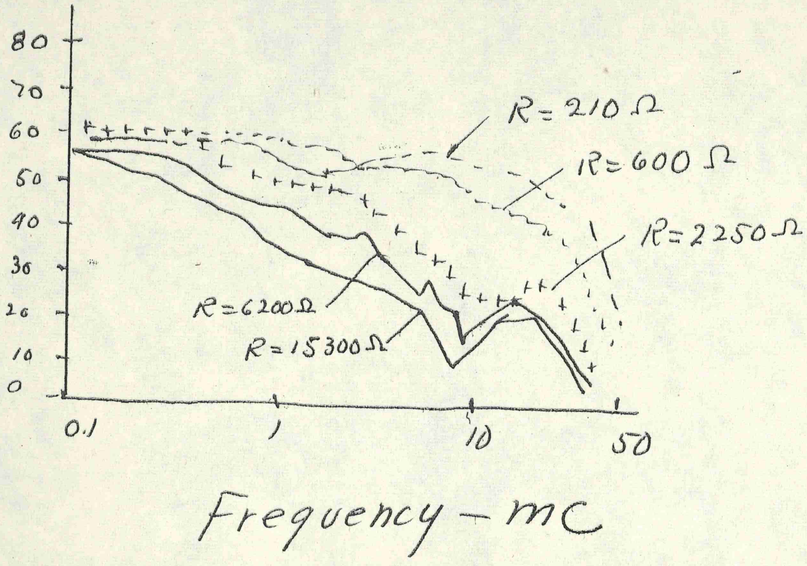
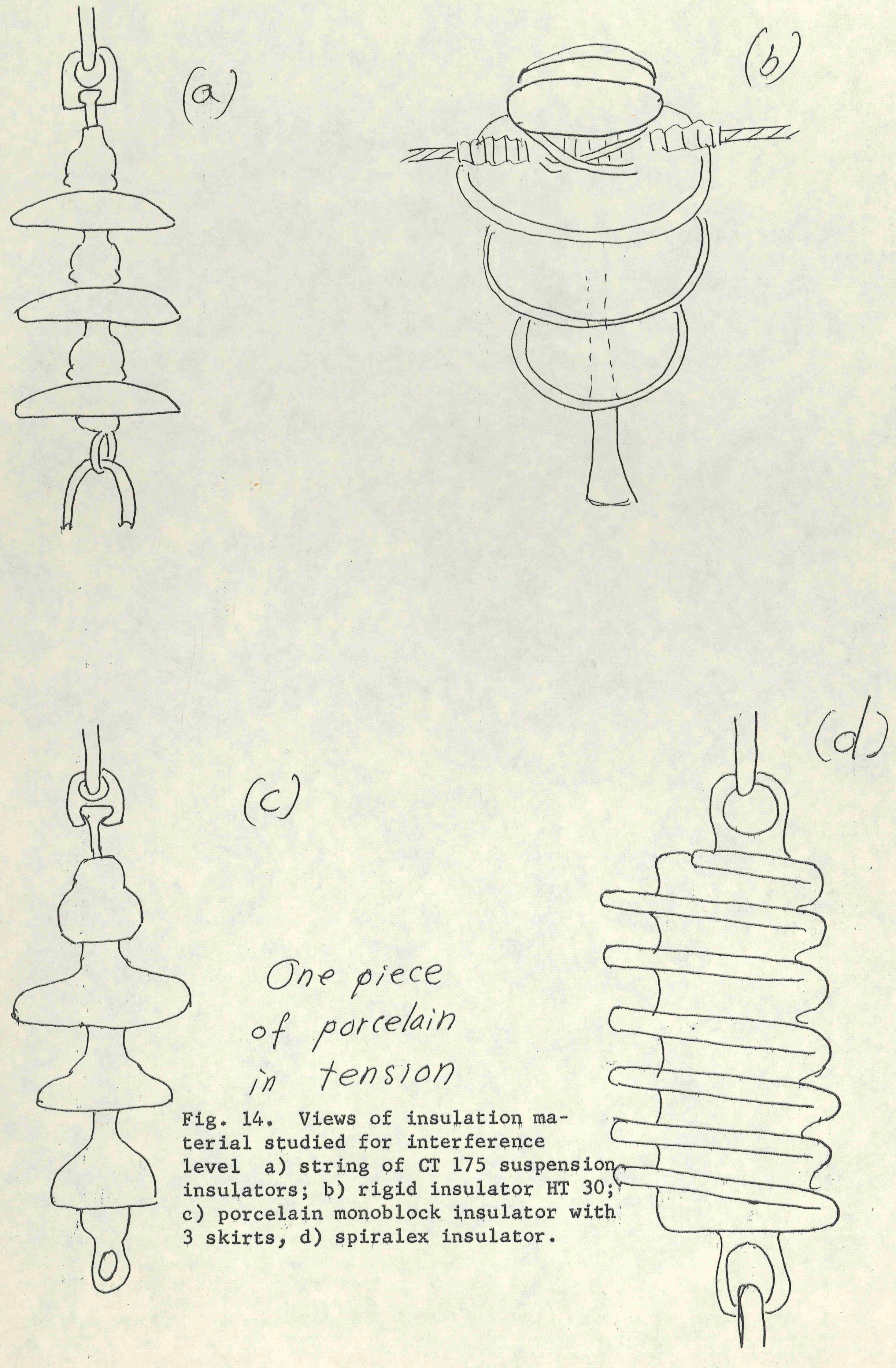


Fig. 13. Spectra of the current for various values of resistor R, generated by artificial pulses repeated at rate of 100 per second, applying to a CT 175 insulator.



One piece
of porcelain
in tension

Fig. 14. Views of insulation material studied for interference level a) string of CT 175 suspension insulators; b) rigid insulator HT 30; c) porcelain monoblock insulator with 3 skirts, d) spiralex insulator.

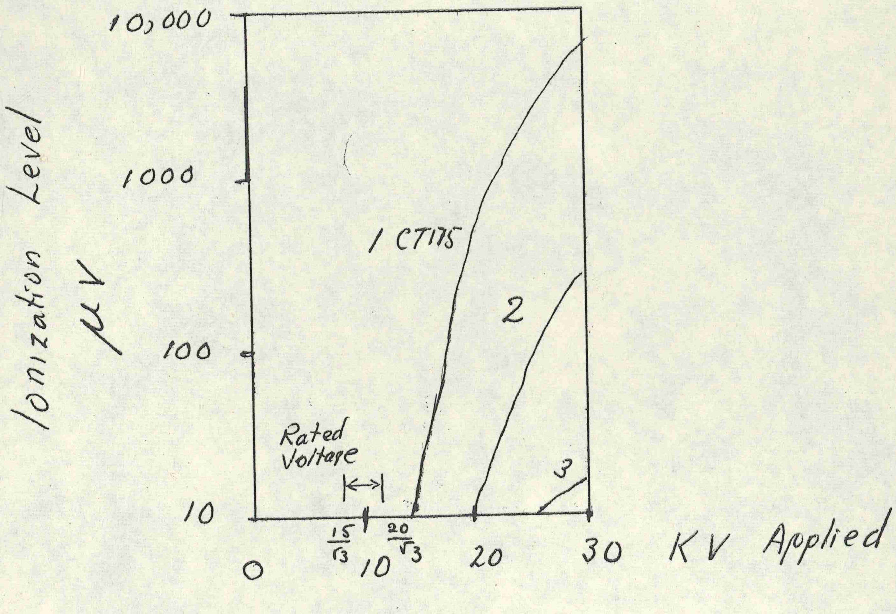


Fig. 15. Curves of disturbance level as a function of voltage for strings of 1, 2, or 3 CT 175 insulators.

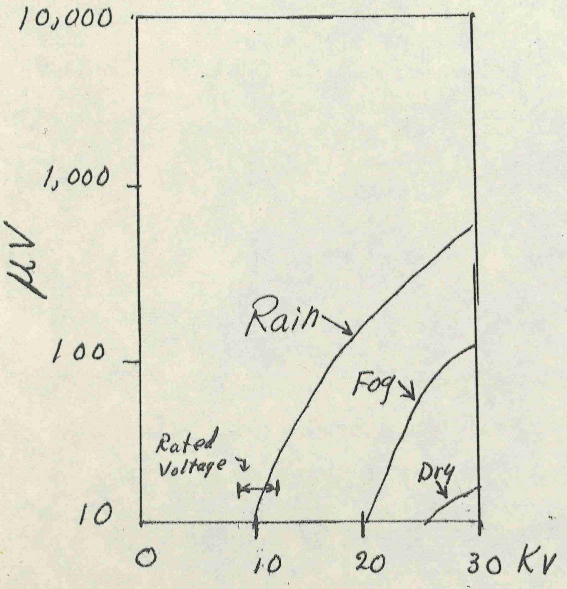


Fig. 16. Curves of disturbance level as a function of voltage for a string of 3 CT 175 insulators for different climactic conditions.

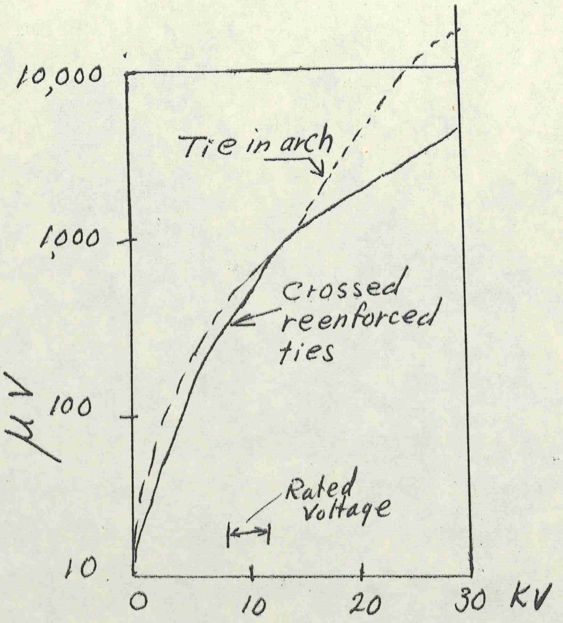


Fig. 18. Curves of the ionization level as a function of voltage, showing the influence of the method of tying on the disturbance level for HT 30 rigid insulators.

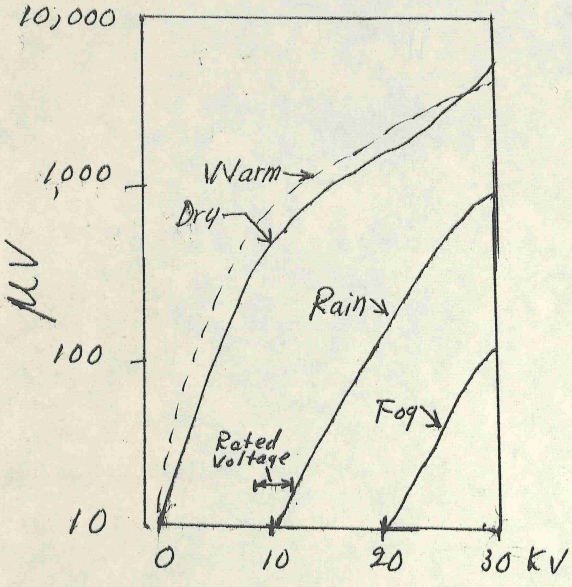


Fig. 17. Curves of disturbance level as a function of voltage for an HT 30 rigid insulator for different climactic conditions.

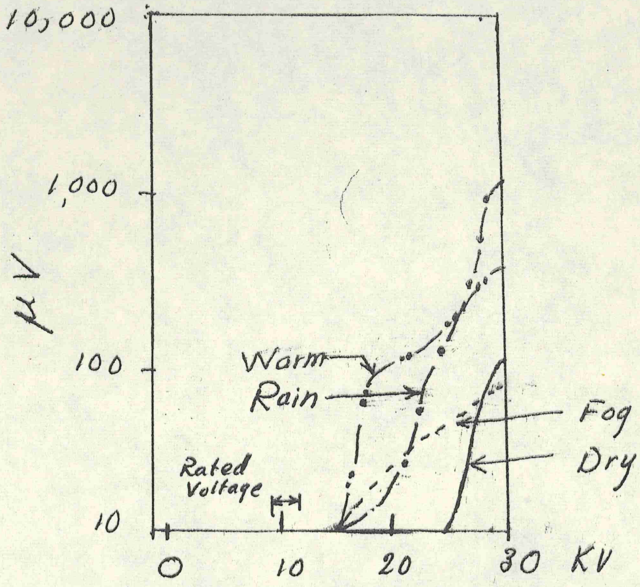


Fig. 19. Curves of the disturbance level as a function of voltage for an Isobloc insulator with 3 skirts for different climactic conditions.

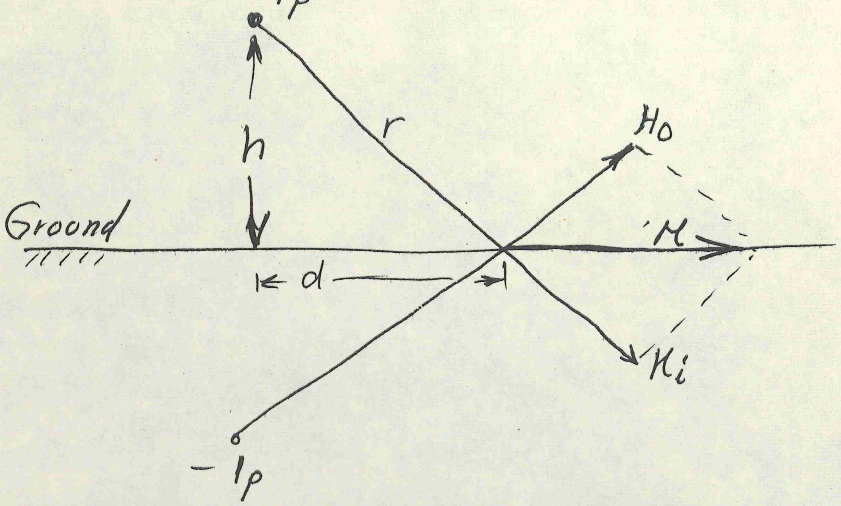


Fig. 20. Calculation of the homopolar disturbance field of a medium voltage line.

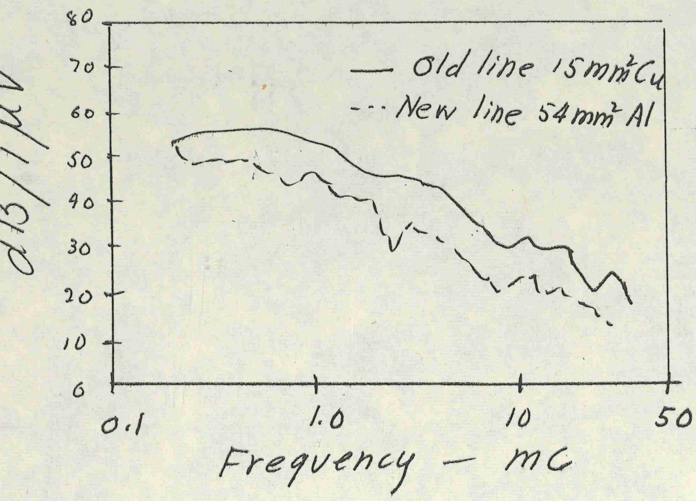


Fig. 21. Spectra of the magnetic component of the disturbance field taken beneath two lines with rigid insulators at 15 kv.

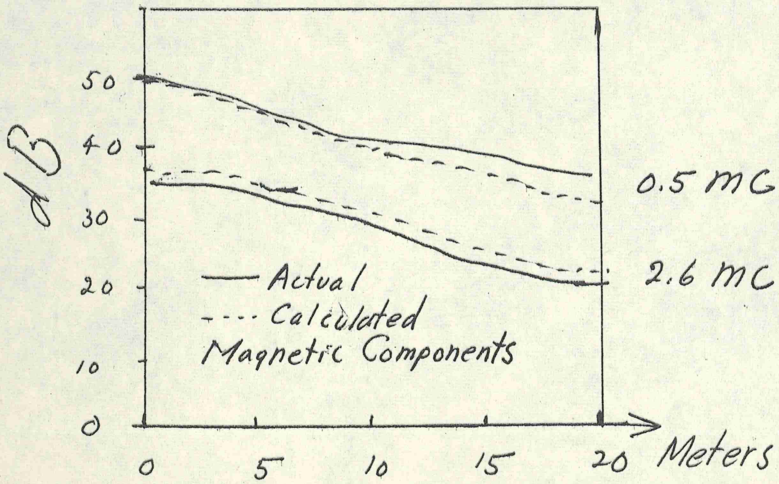


Fig. 22. Actual and calculated profiles of the disturbance field of a 15-kv line.